Sensing and Awareness in Microsystems

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Technology Office

Report Documentation Page

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MTO: Sensing Across the Spectrum

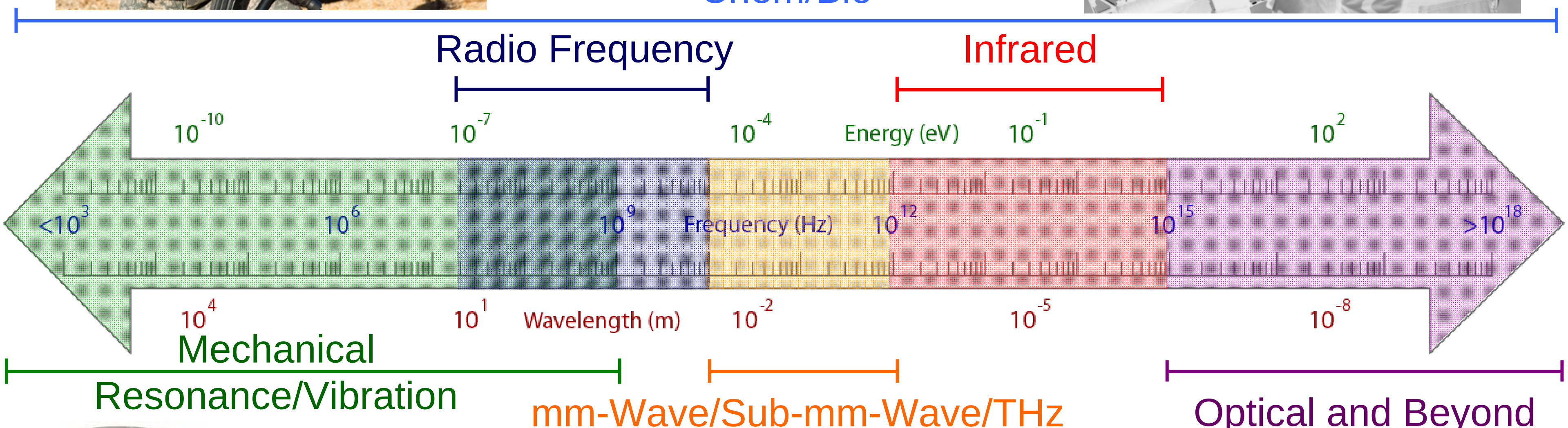
Dr. Sanjay Raman
MTO Symposium
San Jose, CA

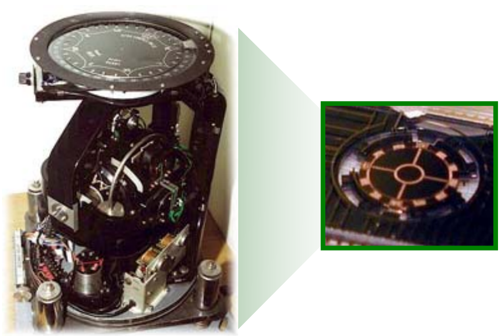
March 4, 2009

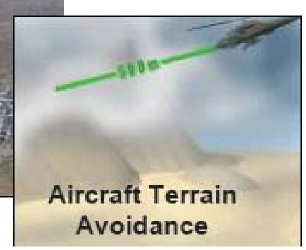
MICROSYSTEMS TECHNOLOGY OFFICE

Sensing the Spectrum: Introduction

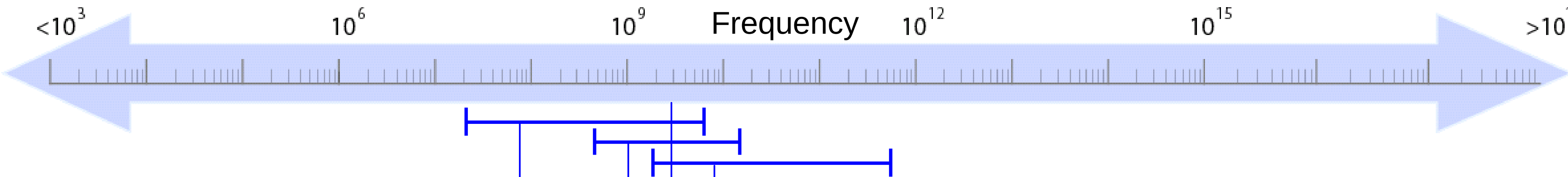
Chem/Bio







Sensing the Spectrum: Radio Frequency



Feedback Linearized Amplifier for RF Electronics (FLARE) *Raman*
Amplifiers for ultra high dynamic-range RF systems

Chip Scale Spectrum Analyzer (CSSA) *Polla*
High Q (>100,000) resonators at 3 GHz for spectrum analysis

Linear Photonic RF Front-End Technology (PHOR-FRONT) *Esman*
Photonic 0.5 – 18 GHz RF front-end

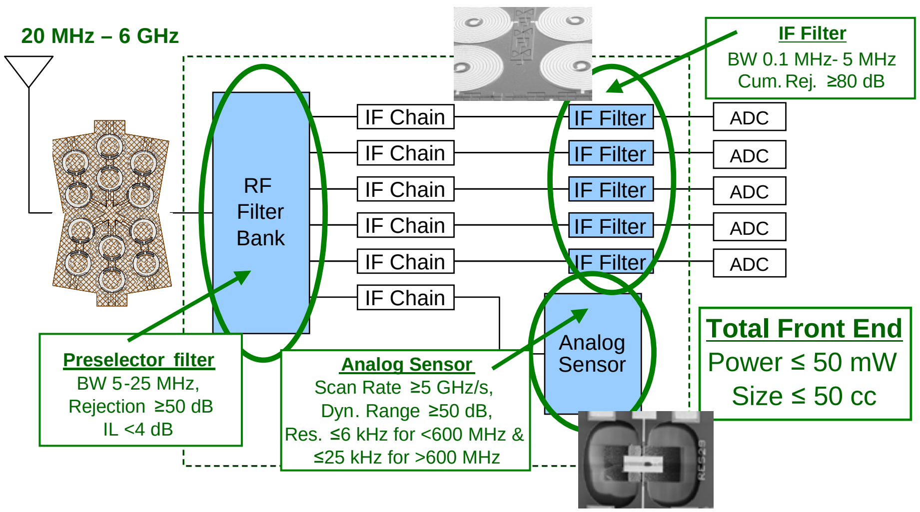
Analog Spectral Processors (ASP) *Raman*
MEMS RF Pre-Select and Sensor Filters from 20 MHz – 6 GHz

Key DoD Applications:
- Cognitive Radio
- Electronic Warfare
- RADAR
- Counter-IED

MTO programs pushing sensitivity, selectivity and dynamic range of RF receivers over wide bandwidths

Recent Accomplishments: Radio Frequency Sensing

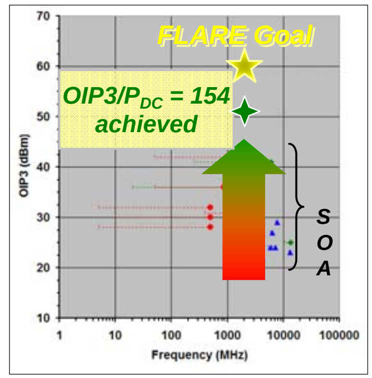
Analog Spectral Processors (ASP)
PM: Sanjay Raman

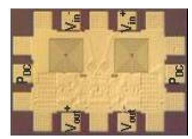


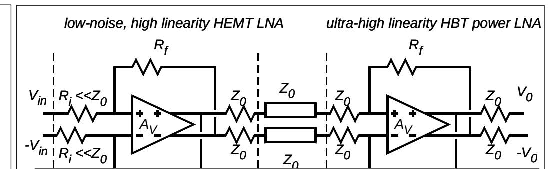
Program Objectives
- Low volume, high-Q pre-select filters covering bands over the 20 MHz – 6 GHz range with independently-tunable 25 kHz bandwidths
- IF filters with tunable BW from 0.1 – 5 MHz
- Analog sensor with 5 GHz/s scan rate

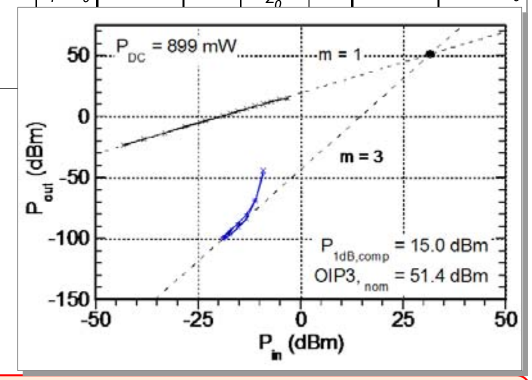
Recent achievements: parallel banks of tunable 3-6 GHz evanescent cavity filters with <4dB IL, high Q Ag inductors and V-caps enable compact high-Q VHF and IF filters

Feedback Linearized Amplifier for RF Electronics (FLARE)
PM: Sanjay Raman









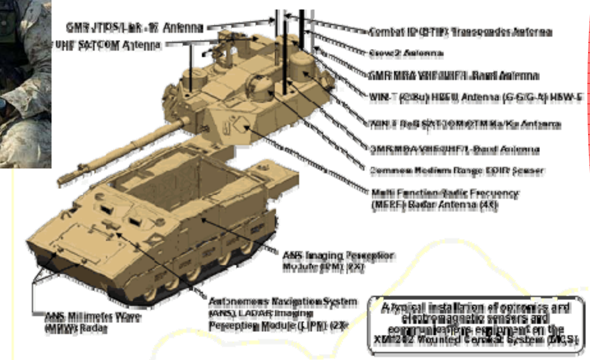
Program Objectives
- Radically improve RF amplifiers' OIP3 for high-dynamic range EW/ELINT receivers
- Ultra-low noise InP HEMT LNAs, ultra-high linearity HBT LNAs, and all-HBT monolithic ultra-high linearity broadband LNAs

Recent achievements: microwave operational amplifiers with +51.4 dBm OIP3, 5.8 dB Noise Figure, 0.9 W @ 2 GHz & 20 dB gain up to 20GHz bandwidth

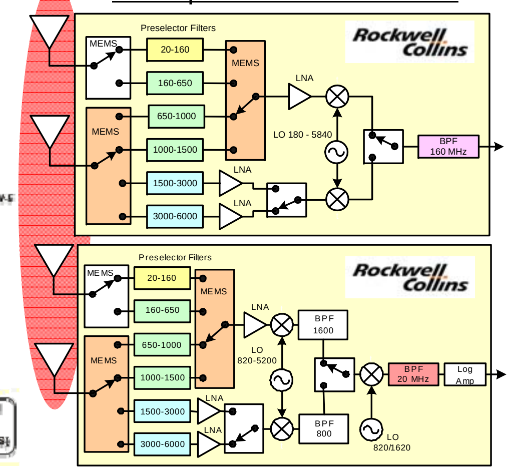
On the Horizon: Antennas

Wideband Antenna Dilemma

A wideband cognitive radio front-end can be miniaturized through high-Q MEMS filters and highly integrated RFICs → however, conventional antennas lead to a *>10-100x* increase in overall volume



Example ASP Architecture



Challenges

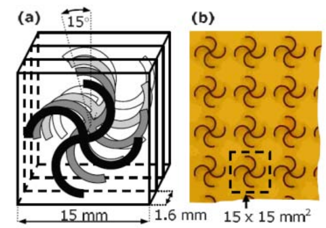
- Chu-Harrington limit → electrically small antennas have poor radiation efficiency, narrow bandwidth
- Impossible to cover a wide bandwidth (such as VHF to S-band) in a single, small volume antenna

Opportunities for Research

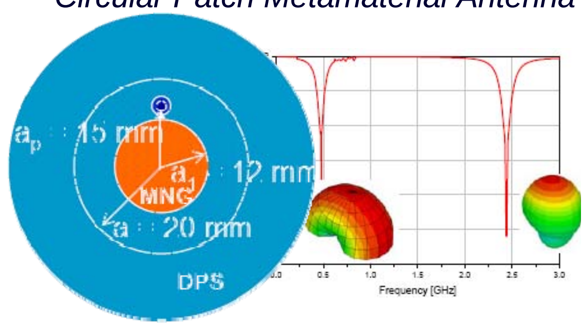
- Adaptive form-factor antennas
- Small antennas for low-frequency
- Active/non-Fosters antennas
- New materials/metamaterials

Multi-layer Chiral Metamaterial Structure

E. Plum, et al. Phys. Rev. B (2009)

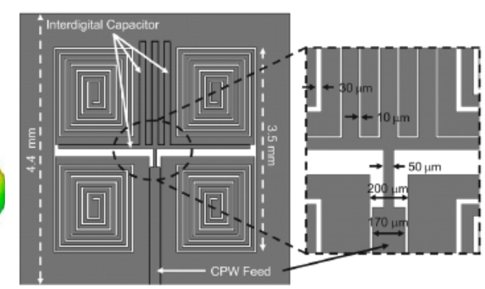


Electrically Small (0.03 λ @ 0.5 GHz) Circular Patch Metamaterial Antenna



F. Bilottii, et al. EuCAP Nov. 2006

Electrically Small (0.03 λ @ 2.45 GHz) Slot Antenna

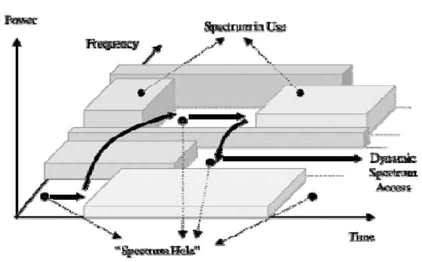


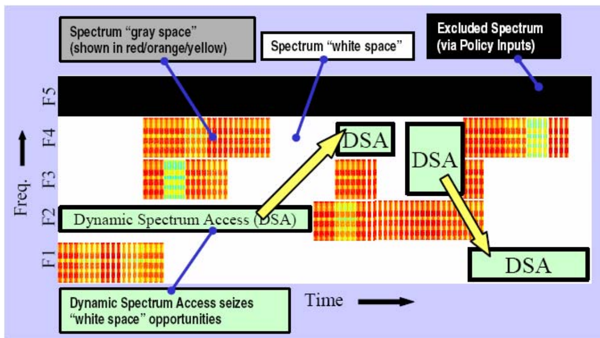
K. Van Caekenberghe, et al. IEEE Ant .and Wireless Prop. Letters 2008

On the Horizon: Cognitive Radio

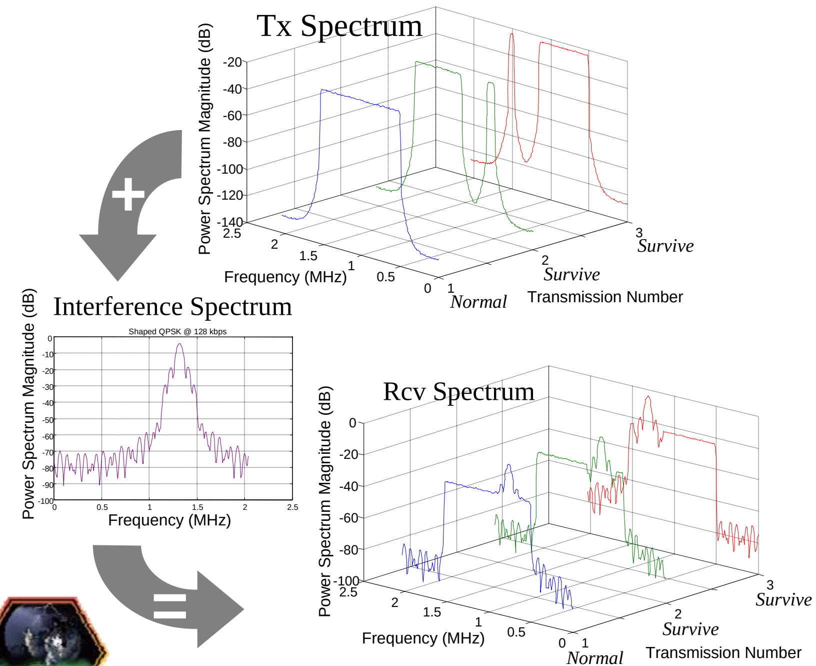
COGNITIVE RADIO: "An approach to wireless engineering wherein the radio, radio network, or wireless system is endowed with *awareness*, *reason*, and *agency* to *intelligently* adapt operational aspects of the radio, radio network, or wireless system." [SDR Forum 2008]

Emerging CR Capability: Dynamic Spectrum Access (DSA)



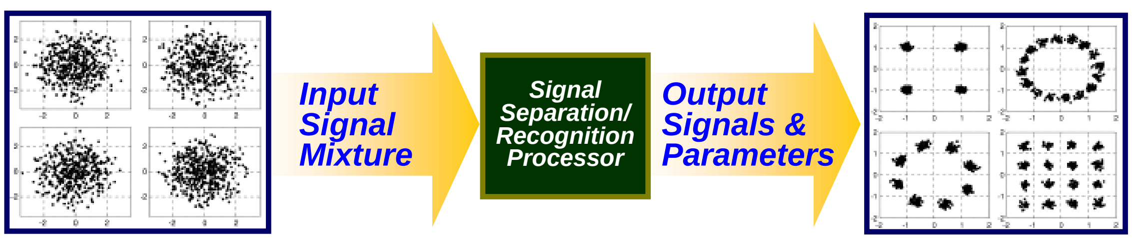


Emerging CR Capability: Interference Detection and Avoidance (DAA)



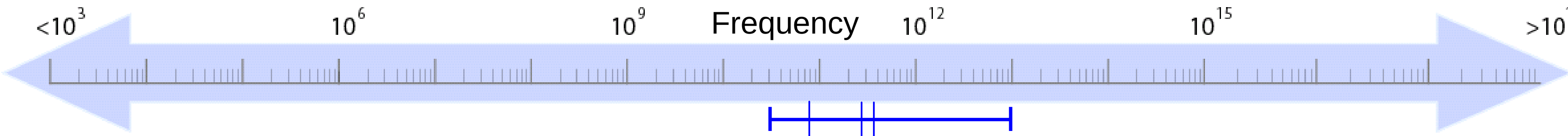
Current CR-related DARPA Programs → energy detection and cooperative/ network-based approaches

Future CR Capability: Low Power Signal Separation and Recognition



TODAY: SOA signal-recognition platforms are large and power hungry. MTO is interested in new, low-power approaches to signal recognition.

Sensing the Spectrum: mm-Wave/Sub-mm-Wave/THz



Microantenna Arrays: Technology and Applications (MIATA) *Kenny*

Microantenna array with sensitivity at 95 GHz

Sub-Millimeter Wave Imaging Focal-Plane Technology (SWIFT) *Rosker*

Active 340 GHz sub-aperture

Terahertz Imaging Focal-plane Technology (TIFT) *Rosker*

Multi-element detector receiver focal plane arrays in the THz band

The next step beyond SWIFT and TIFT →
Dr. Mark Rosker's THz Electronics program

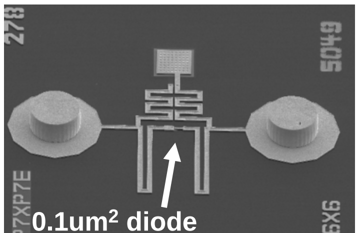
Compact, high-performance circuits that operate at center frequencies > 1.0 THz

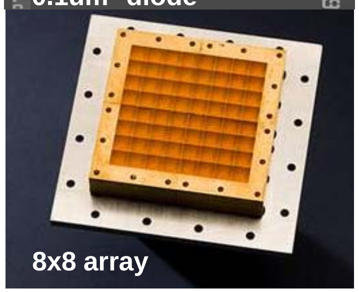
Key DoD Applications:
- Reduced visibility aircraft landing/navigation systems
- Precision munitions guidance
- High-bandwidth data links
- Standoff contraband detection
- Chem/bio detection

MTO is pushing the limits of electronic devices and MMIC technology to >1 THz operation

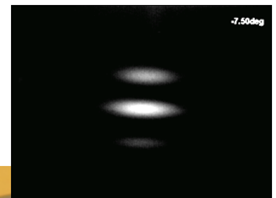
Recent Accomplishments: mm-Wave/Sub-mm-Wave/THz

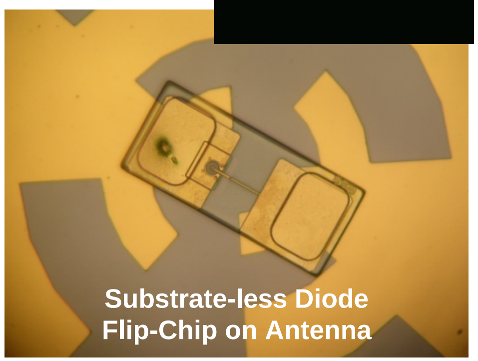
Microantenna Arrays: Technology and Applications (MIATA)
PM: Tom Kenny





First 1-D images





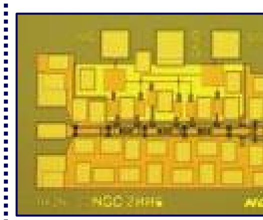
Program Objectives

- Phase-sensitive imaging opens up heretofore impossible mm-Wave applications
- Phase-sensitive detection via optical upconversion to create conformal imaging arrays
- High resolution with large volume reduction

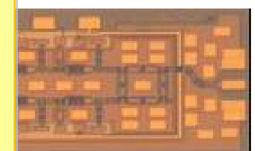
Recent achievement: MMIC-based antenna to detector impedance matching network resulted in world record in sensitivity for mm-Wave detectors

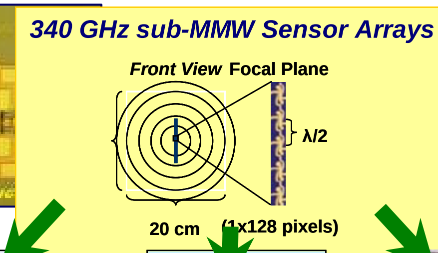
Sub-millimeter Wave Imaging FPA Technology (SWIFT)
PM: Mark Rosker

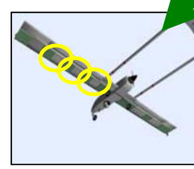
First S-MMW LNA



First S-MMIC PA

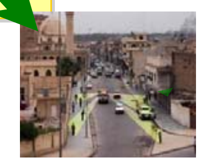






All-Weather Look-Down ISR

All-Weather Terrain Avoidance



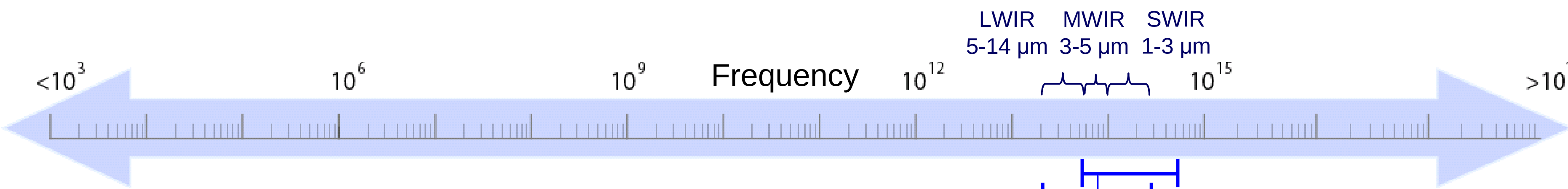
Concealed Weapons Detection at Range

Program Objectives

- Demonstrate world's fastest MMICs for imaging at sub-mm-wave frequencies in a number of all-weather environments and platforms
- Achieve an integrated imaging system consisting of a 1 x 128 pixel active array

Recent achievements: LNA with7.5 dB NF @ 350 GHz with 68 GHz BW (23%); 340 GHz oscillator with PN <-42 dBc/Hz @ 100 Hz

Sensing the Spectrum: Infrared



Photon-Trap Structures for Quantum Advanced Detectors (PT-SQUAD) *Dhar*
Ultra broadband (0.5 to 5µm) highly sensitive focal plane array

Micro Imagers for Sensing (MISI) *Horn*
SWIR micro-camera-on-a-chip

Adaptive Focal Plane Array (AFPA) *Horn*
IR Focal Plane Arrays w/o cryogenic cooling

High Operating Temperature Mid-Wave Infrared (HOTMWIR) *Horn*
IR Focal Plane Arrays w/o cryogenic cooling

Advanced Microsystem Technology Program (AMTP) *Kovacs*
One goals of this multi-faceted program is 3D integration of new sensor materials for MWIR avalanche photo detector arrays

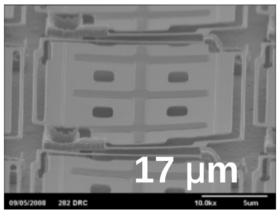
Key DoD Applications:
- Night Vision systems
- Low ambient light imaging
- Early warning
- Contraband detection

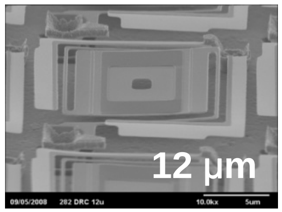
MTO has a robust portfolio of sensing and imaging technologies across the IR band → towards hyperspectral imaging

Recent Accomplishments: Infrared Sensing

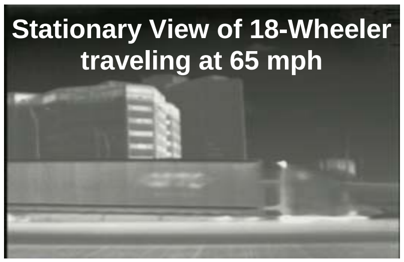
High Operating Temperature Mid-Wave Infrared (HOT MWIR) PM: Stuart Horn

Thermal detectors with wavelength-size features





Fast scene capture with 12 µm 1024 x 768 FPA with thermal time constant of ~7 ms

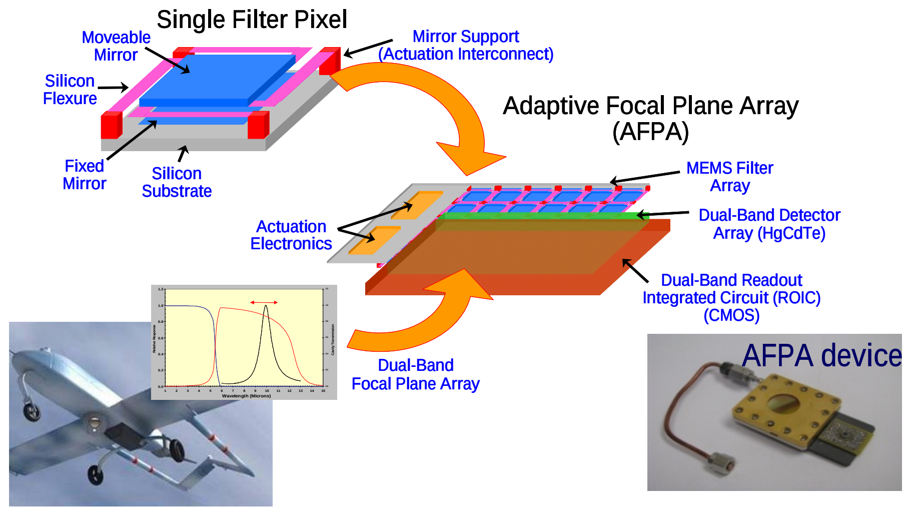


Program Objectives

- Low thermal mass, short time constant pixel enabled by Diffractive Resonant Cavity (DRC) design & low noise, high TCR a-Si/a-SiGe
- Room temp IR for small platform persistent surveillance & distributed aperture threat warning

Recent achievements: 12 µm 1024 x 768 imaging demonstration with NETD ~50 mK → capture of < 3 ms fast events

Adaptive Focal Plane Array (AFPA) PM: Stuart Horn

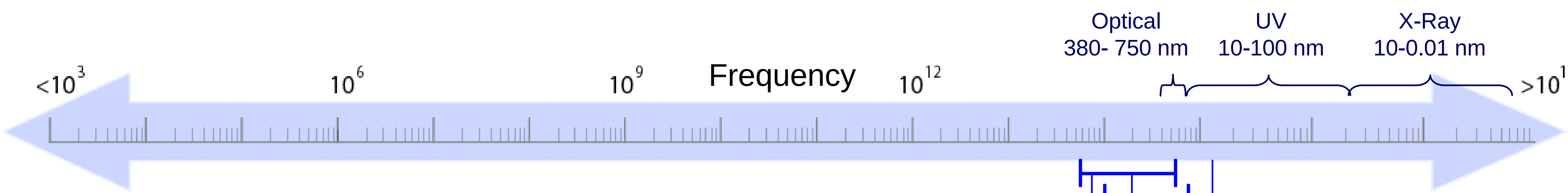


Program Objectives

- Integrate tunable MEMS filters w/ dual-band FPA
- Enable target classification based on LWIR spectral signatures in chip-scale device
- Enable detection of buried mines (IEDs) and camouflaged targets from tactical (UAV) platform

Recent achievement: demonstrated narrow band (100 nm) spectral tunable Focal Plane Array from 8 – 11 µm in chip-scale package

Sensing the Spectrum: Optical and Beyond



Photon-Trap Structures for Quantum Advanced Detectors (PT-SQUAD) *Dhar*
Ultra broadband (0.5 to 5µm) highly sensitive focal plane array

Photon Counting Arrays (PCAR) *Horn*
Low level illumination imaging from visible through SWIR

Hemispheric Array Detector for Imaging (HARDI) *Shenoy*
400-1900 nm pixelated photodetector array

Deep Ultraviolet Avalanche Photodetectors (DUVAP) *Temkin*
APDs operating in Geiger mode centered at 280 nm

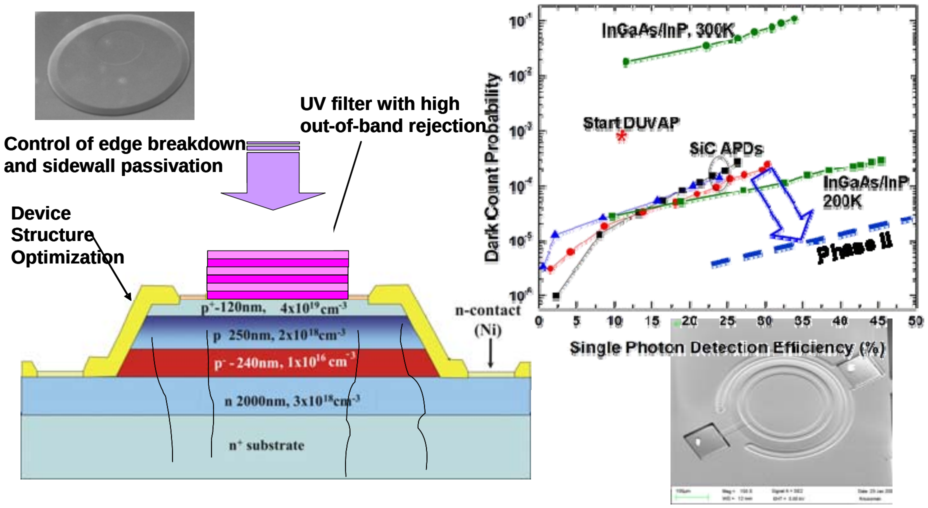
Multiple Optical Non-Redundant Aperture Generalized Sensors (MONTAGE) *Healy*
Co-design and joint optimization of the optical, detection, and processing aspects of imagers

Key DoD Applications:
- UAV cameras
- Low ambient light imaging
- High-data rate Optical/UV Comms

MTO has a strong portfolio in visible and low-light imaging, including exploiting advanced signal processing algorithms for revolutionary imaging capabilities

Recent Accomplishments: Optical and Beyond

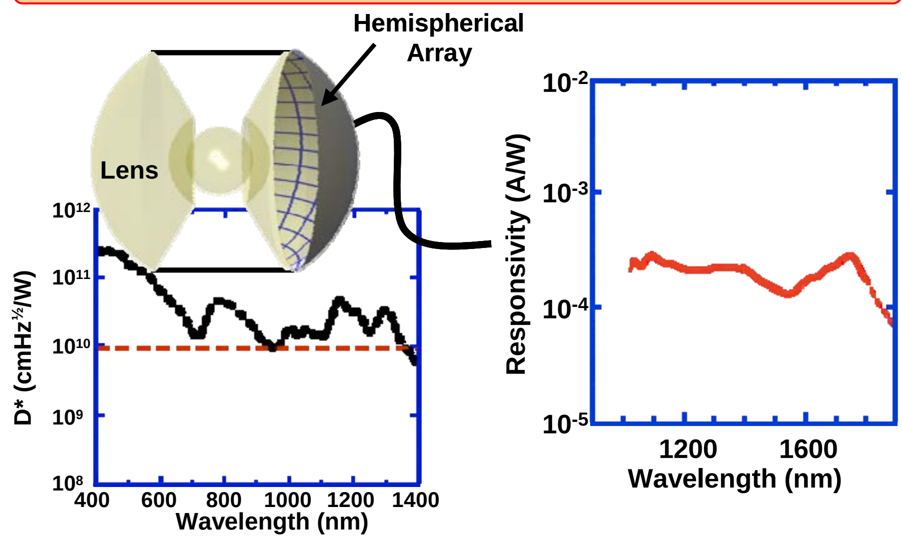
Deep UV Avalanche Photon Detectors (DUVAP)
PM: Henryk Temkin



Program Objectives
- Demonstrate arrays of solar-blind Geiger mode avalanche photodetectors.
- Single photon detection of the UV spectrum
- Room temp Geiger mode operation of a SiC APD
- Quantum efficiency of 65% @ 280 nm

Recent achievements: Geiger mode demo with quantum efficiency of 65% @ 280 nm & uniform gain > 10,000

Hemispherical Array Detector for Imaging (HARDI)
PM: Dev Shenoy



Program Objectives
- Develop hemispherical focal plane arrays for VIS-NIR-SWIR wavelengths for wide field of view (FOV), simple, and robust imagers
- Eliminate the need for multiple detectors or gimbals thus lessening the system complexity

Recent achievements: responsivity of PD material to 1.9 µm & detectivity of >10^{10} cmHz½/W up to 1400 nm

On the Horizon: Radiation Sensing

DoD needs small, high-sensitivity radiation detectors → Fundamentally conflicting requirements

*→ Require **new materials** with both good absorption and good quantum efficiency*

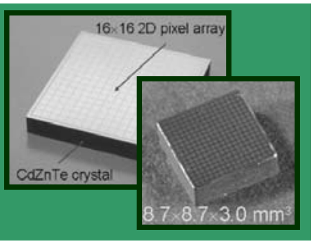
*→ Require **new devices or circuits** to make the most of already existing materials*

Materials and Challenges

HgI2 , PbI2 , GaSe, CdTe, CdZnTe: *Production of large/uniform single crystals, material cost reduction*

GaAs: *Increasing neutron detection efficiency in a high gamma ray environment*

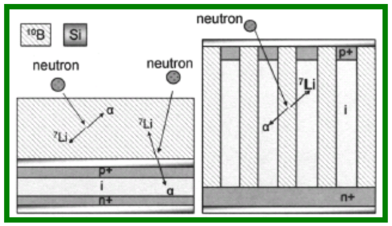
Boron-based neutron detectors: *Bulk crystal growth and film impurity reduction*



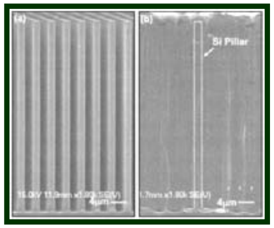
Emerging Device Structures and Circuits

Pillar Structured, 3D Neutron Detector (Livermore Natl. Lab)

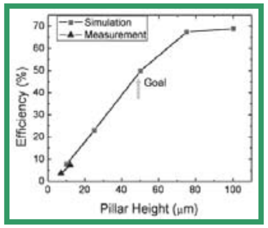
SOA 2D Device **3D Device**



Prototype 3D Device



Goal & Performance

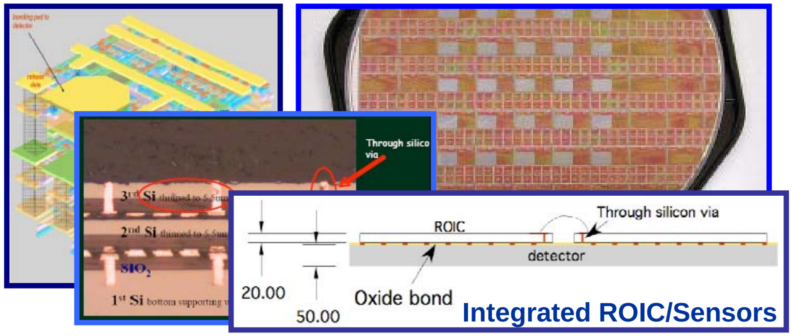


•*Device design takes advantage of high ¹⁰B neutron cross section while overcoming limitations of SOA 2D device geometry*

•*Prototype device shows 7.3% efficiency →device scaling for high efficiency is feasible*

3D ICs for Particle Detection (Fermilab/MIT LL)

3DIC design for HEP **Fabricated HEP Sensors**



- *First HEP detector using SOI-based 3DIC technology*
- *Developing sensor integration technologies for stacked sensor/ROIC integration*

DARPA MTO is interested in new ideas for compact, high-sensitivity radiation detectors

Sensing the Spectrum: Mechanical Resonance/Vibration

<10^3 | 10^6 | 10^9 | Frequency | 10^12 | 10^15 | >10^18

Chip-Scale Atomic Clock (CSAC) *Lal*
60 kHz clock from 9 GHz Cesium Standard

Hybrid Insect MEMS (HI-MEMS) *Lal*
Acoustic and ultrasonic sensors mounted to insect platforms

Compact Ultra-Stable Gyro for Absolute Reference (COUGAR) *Lal*
Fiber optic resonator gyroscope architecture for ultra-high precision rotation sensing

Micro Inertial Navigation Technology (MINT) *Lal*
Combination of microscale inertial and velocity sensors for inertial navigation

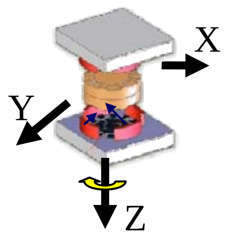
Navigation-Grade Integrated Micro Gyroscopes (NGIMG) *Lal*
Inertial Sensors with 300 Hz BW

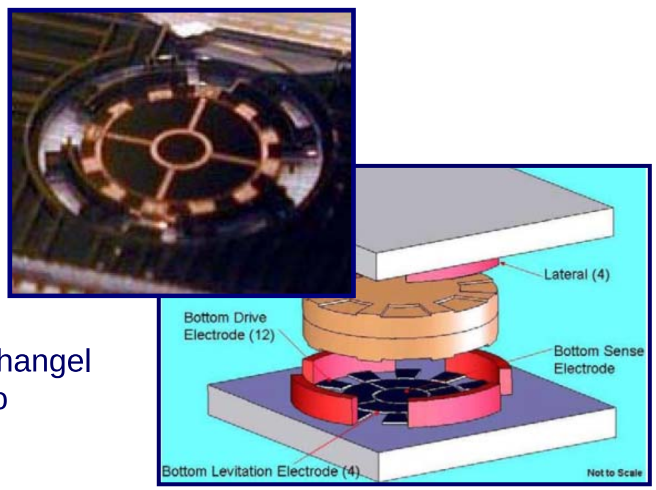
Key DoD Applications:
- Ultra-stable clock references
- Miniaturized inertial grade navigation
- GPS-denied navigation
- Covert sensing with bionic platforms
- Underwater surveillance/SONAR

Sensing of mechanical and atomic vibrations/resonances leads to ultra-precise navigation and timing

Recent Accomplishments: Mechanical Resonance/Vibration

Navigation-Grade Integrated Micro-Gyroscopes (NGIMG)
PM: Amit Lal





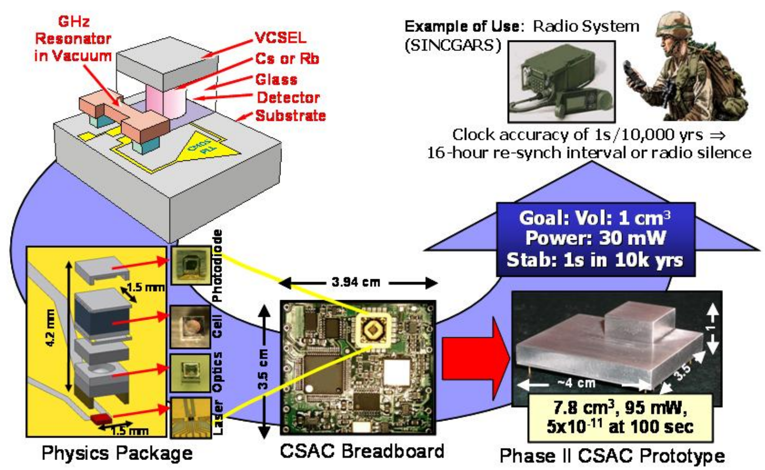
Example: Archangel Spinning Gyro

<u>Program Objectives</u>

- Attain tiny gyros and accelerometers with navigation-grade performance and tiny power consumption
- Achieve ultrahigh quality factor resonators ($Q>10^7$), miniature NMR, and spinning masses

Recent achievement: devices spinning at 200 rpm (20.9 rad/s) for over 2 hours in a 6 mT vacuum package

Chip-Scale Atomic Clock (CSAC)
PM: Amit Lal

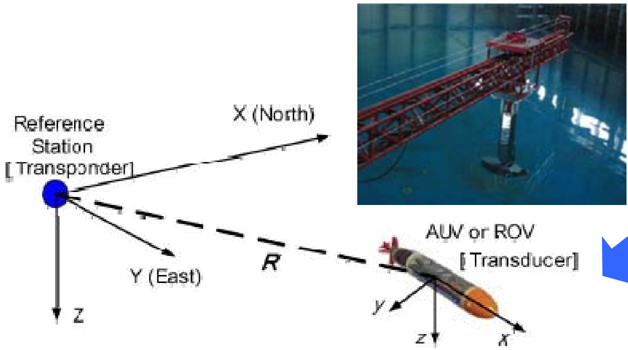


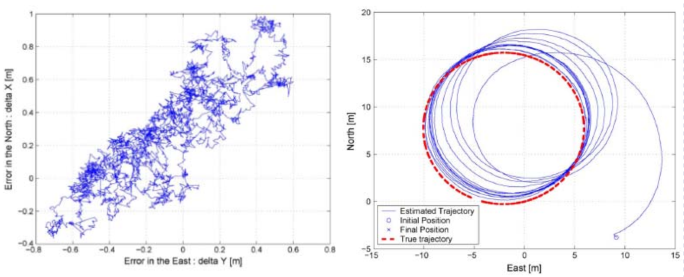
<u>Program Objectives</u>

- Integrate MEMS, photonic, and electronics technologies to achieve miniature, low-power atomic timing and frequency references with:
- Allan deviation < 10-11 over 1 hour (1 ms/day)
- Size < 1 cc & Power Consumption < 30 mW

Recent achievement: long-term frequency stability of -2x10^{-8} seconds/day & short term stability of 4x10^{-11} / $\sqrt{\tau}$

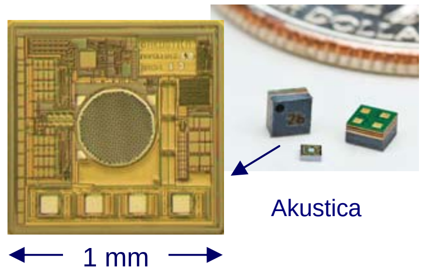
On the Horizon: Acoustic Sensing





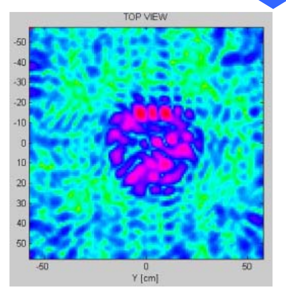
Inertial Acoustic Nav System for UUV

Lee et al, IEEE Journal of Oceanic Engineering (Apr 2007)



Akustica

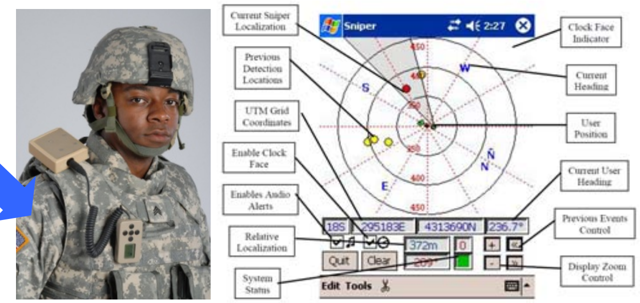
Potential for Embedding MEMS Microphones in new applications



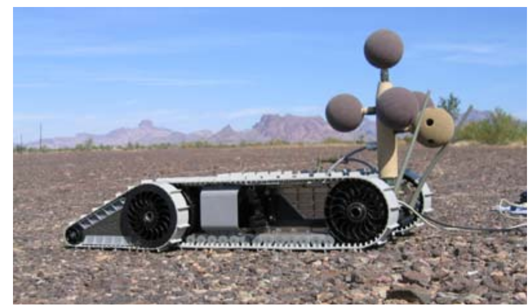
Acoustic Imaging of 3D Objects

Palmese et al, IEEE Trans. Inst. Meas. (Apr 2008)

Acoustic Sniper Localization



QinetiQ EARS



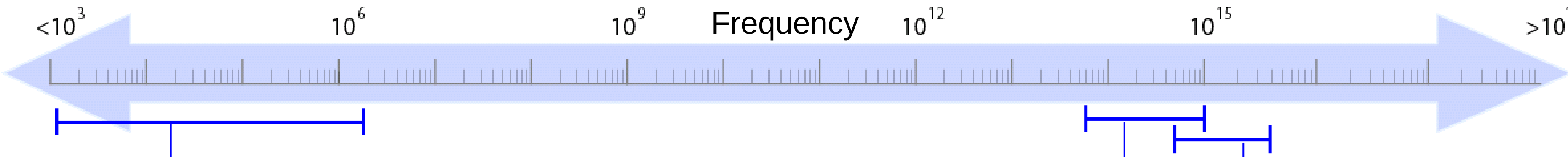
Robertson et al. Proc. SPIE (2006)

Opportunities for Research

- Sound localizers and identifiers
- High frequency ultrasound sensors for imaging/ material characterization
- Underwater acoustic sensors/UUV SONAR arrays
- Advanced chemical detection through photo-acoustic sensing

Acoustic sensing has a wide variety of potential applications – recent advancements in materials and MEMS technologies can be brought to bear on problems in this area

Sensing the Spectrum: Chem/Bio



SERS S&T Fundamentals *Polla*
Nanoparticle optical antennas for chemical detection

Laser Photoacoustic Spectroscopy (L-PAS) *Temkin*
Acoustic chemical detection via IR laser excitation

Recognize IED and Report (RIEDAR) *Shenoy*
HazMat standoff detection with spectroscopic techniques

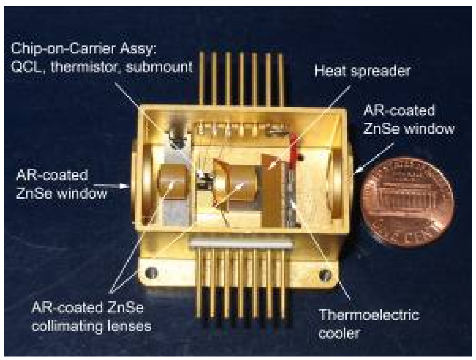
Micro Gas Analyzers (MGA) *Polla*
Tiny separation analyzer-based chemical warfare agent (CWA) sensors

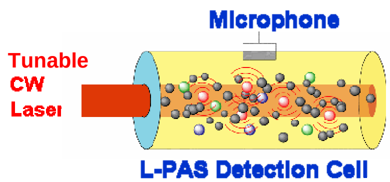
Key DoD Applications:
- Counter IED
- Chem/Bio Warfare agent detection
- Contraband detection
- Biomedical analysis in the field

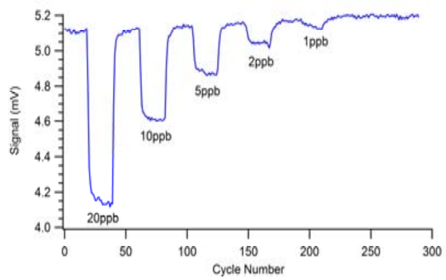
MTO has a growing portfolio in chemical sensing, from fundamental materials and device investigations, to compact MEMS-based analysis platforms

Recent Accomplishments: Chem/Bio Sensing

Laser Photoacoustic Spectroscopy (L-PAS)
PM: Henryk Temkin



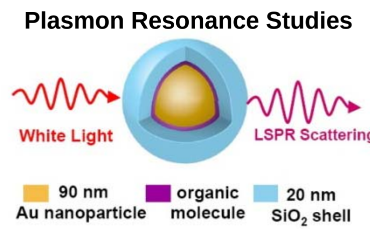


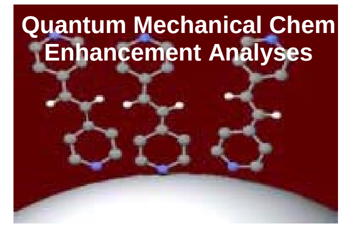


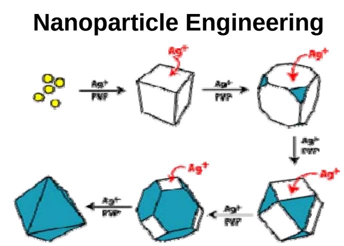
Program Objectives
- Single mode quantum cascade lasers > 200 mW output power with 400 nm tunability and a PAS system with 1 ppb sensitivity for DMMP
- Compact, rapid, reliable and highly sensitive chemical warfare agent (CWA) sensors

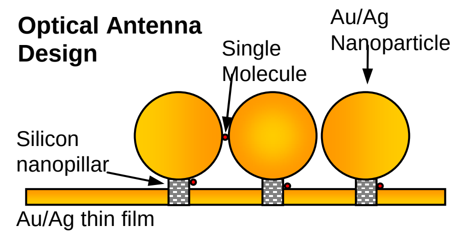
Recent achievement: Dimethyl Methylphosphonate (DMMP) detection with a 10.5 μm Quantum Cascade Laser; sensitivity ~ 1 ppb

Surface Enhanced Raman Spectroscopy S&T Fundamentals PM: Dennis Polla







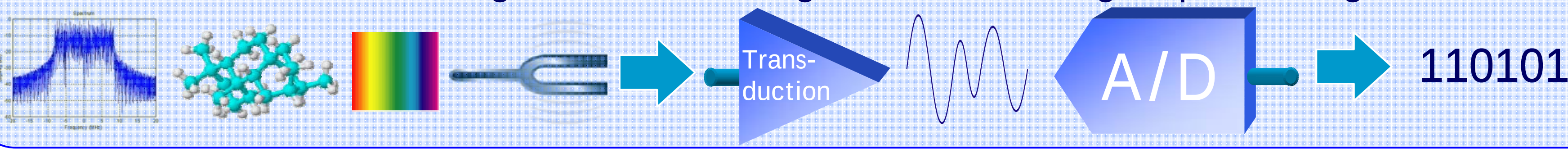


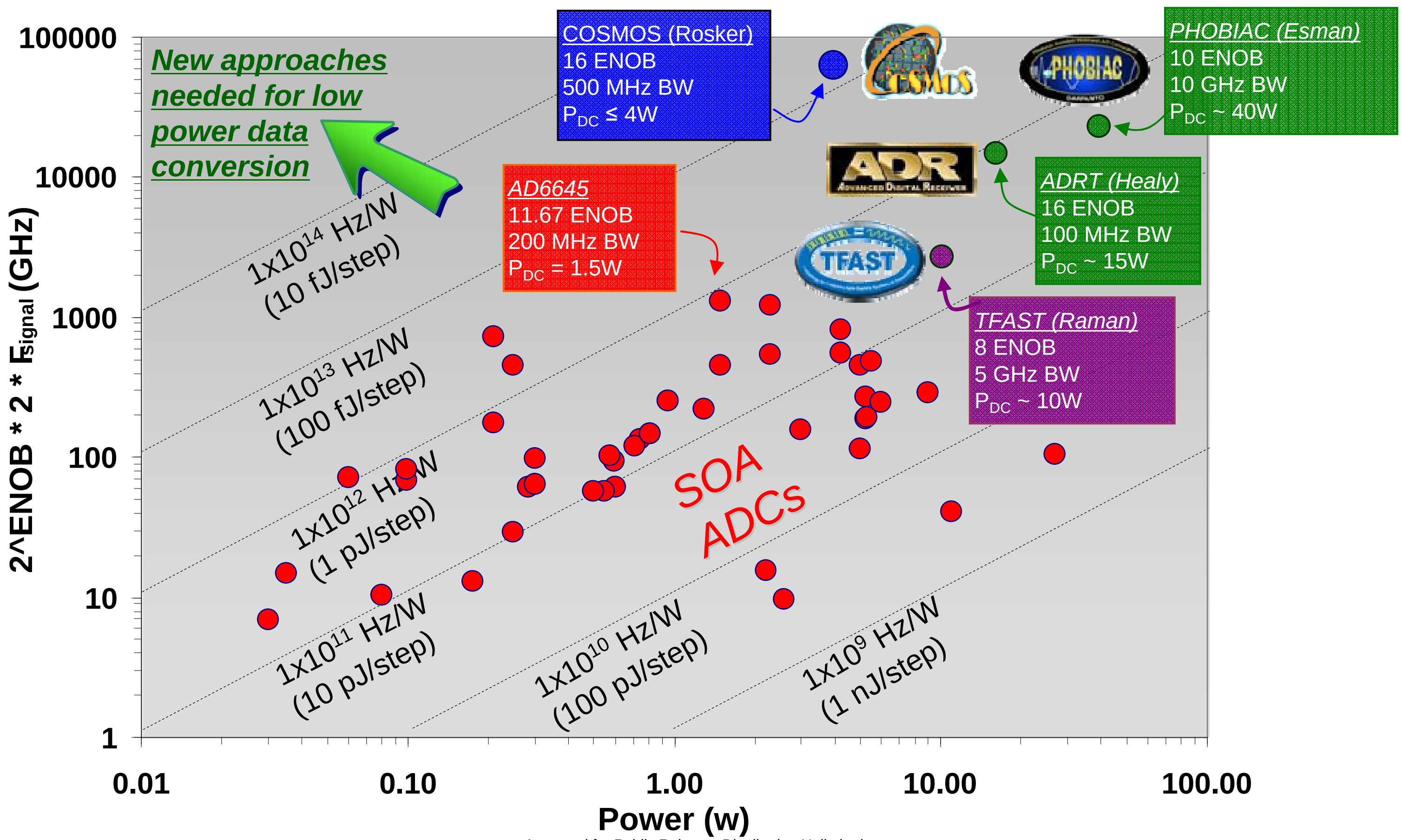
Program Objectives
- Enhancement factors of 10^{12} for liter-sized nanoparticle samples or 28 in^2 nano-array wafers
- Achieve reproducible performance of nanoparticles and nano-arrays and optimize characterization methods

Recent achievement: nano-antenna design has achieved reproducible surface Raman spectroscopy enhancement factors of 10^7

Analog-to-Digital Conversion

An important aspect of sensing is converting the collected information from the analog domain to the digital domain for signal processing



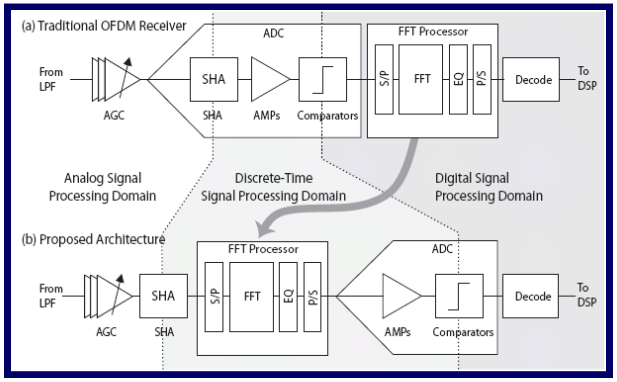


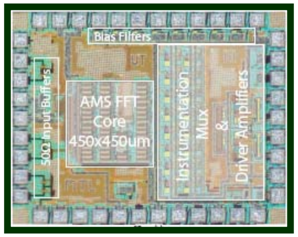
On the Horizon: Low-Energy Data Conversion

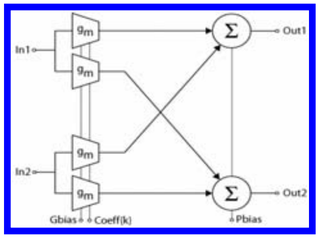
Potential Approaches:

- *Sub-threshold: Circuit designs based on transistors operating below V_{th}.*
- *Charge-Based: Passes charge packets between stages like a CCD, rather than amplifying with op amps at each stage.*
- *Zero-Crossing: op-amps are replaced with a current source and a zero-crossing detector.*
- *Analog Signal Processing: Performs computationally intensive operations in analog/discrete-time domain.*

Low-Energy, Discrete-Time Analog OFDM Rx



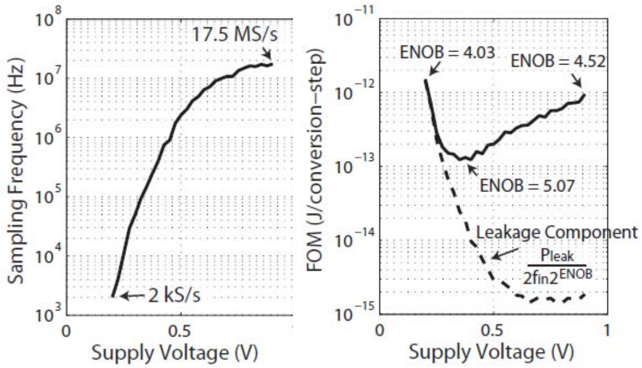


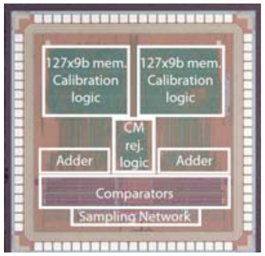


- FFT moved in front of the ADC, relaxing ADC resolution requirements
- FFT implemented using a single, repeatable butterfly circuit
- *Order of magnitude lower power consumption than equivalent ADC /DSP-based approach*

M. Lehne et al, 2008 IEEE RWS (Jan 2008)

6b 0.2-to-0.9 V Sub-Threshold ADC





- ADC FOM of 125 fJ/step achieved at 0.4 V sub-threshold supply voltage
- Device variation is a key design challenge at low supply voltages

D. Daly et al, ISSCC (Feb 2008)

DARPA MTO is interested in new approaches to achieve high ADC performance at ultra-low energy.

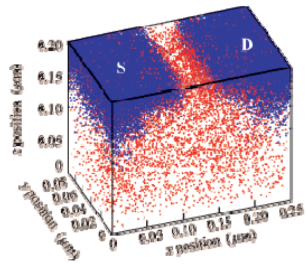
On the Horizon: On-Chip Sensing

A Consequence of Scaling

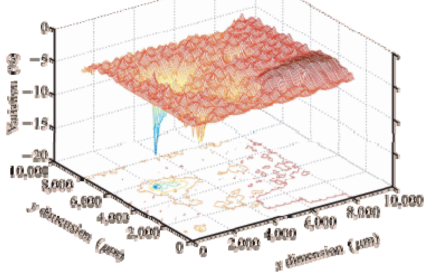
Severe inter- & intra-die variations in process parameters, voltage and temperature (PVT) in deeply scaled technologies result in performance “left on the table”

On-chip sensors measure impact of variability → in situ control loops drive the circuit back to required specifications

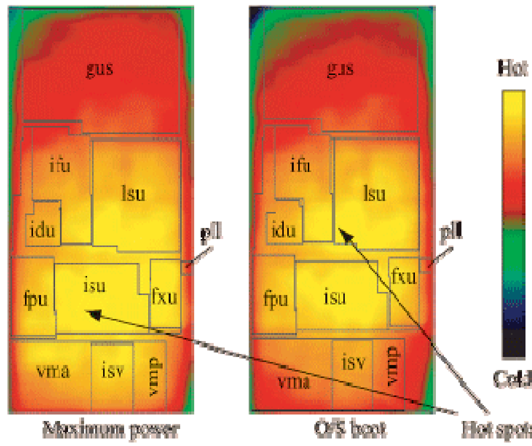
Process doping variations



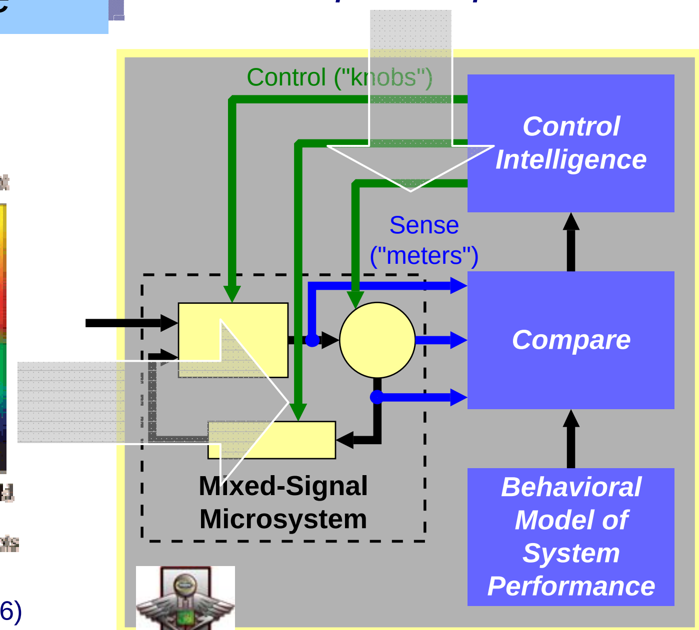
Variable supply voltage



Temperature variations



K. Bernstein, et al. IBM J. Res. & Dev. (2006)

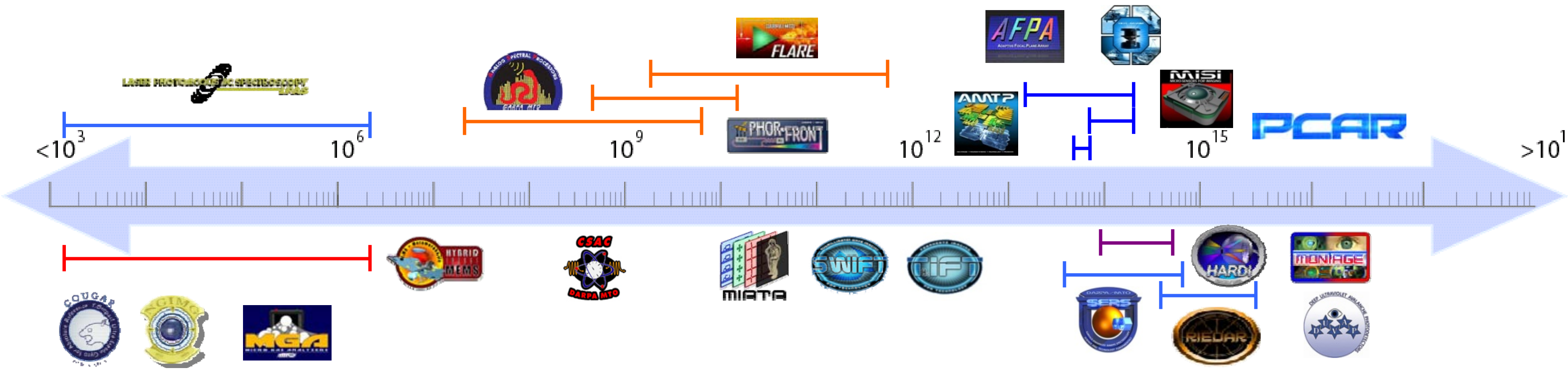


DARPA HEALICs program
Kicking off later this March

Opportunities for Research

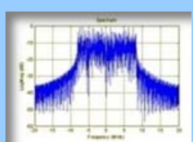
- Novel on-chip variability sensors and actuators for dynamic performance correction
- Robust/stable control algorithms, hardware implementations subject to variability
- Design methodologies/EDA tools for self-healing circuits

MTO:
Sensing Across the Spectrum



MTO programs are pushing the limits of sensing from atomic vibrations to optical wavelengths and beyond

DARPA and the DoD need your innovative ideas for



"Sensing across the Spectrum"

✸Contact an MTO program manager to discuss your ideas

✸Or consider becoming a PM yourself… ***…Join Us!***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